Research Papers
Issue RP0201
December 2013

CIP - Climate Impacts and Policy Division

Network Economics and the Environment: Insights and Perspectives

By **Sergio Currarini**
Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC),
Department of Economics,
University of Leicester
sc526@le.ac.uk

Carmen Marchiori
Department of Geography and Environment, London School of Economics and Political Science,
Grantham Research Institute on Climate Change and the Environment,
Fondazione Eni Enrico Mattei (FEEM), Houghton Street,
London WC2A 2AE, UK.
c.marchiori@lse.ac.uk

Alessandro Tavoni
Grantham Research Institute on Climate Change and the Environment,
London School of Economics and Political Science,
Fondazione Eni Enrico Mattei (FEEM), Houghton Street,
London WC2A 2AE, UK.
a.tavoni@lse.ac.uk

SUMMARY Recent research in the field of network economics has shown how explicitly modelling the network structure of social and economic relations can provide significant theoretical insights, as well as account for previously unexplained empirical evidence. Despite their critical importance to many environmental problems, network structures and dynamics have been largely disregarded by the environmental economics literature. This paper aims to begin to fill this gap by analysing how networks can provide new insights for both theory and practice, and identifying several avenues for future research. The paper addresses questions pertaining to a wide range of issues, including the adoption and diffusion of green technologies, access to and distribution of natural resources, common-pool resource management and governance, and the stability of international environmental coalitions.

Keywords: Networks, Environmental Externalities, Technological Diffusion, Gas Pipelines, Common-pool Resources, Multi-level Governance, Coalitions

This report represents the Deliverable P21b developed within the framework of Work Package 6.2.3 of the GEMINA project, funded by the Italian Ministry of Education, University and Research and the Italian Ministry of Environment, Land and Sea.

1 INTRODUCTION

Recent research has shown how explicitly modelling the network structure of social and economic relations can provide significant theoretical insights, as well as account for previously unexplained empirical observations. Relevant areas of application range from labour markets (Calvo-Armentgol, 2004; and Jackson and Calvo-Armengol, 2004), the diffusion of opinions and diseases (Jackson and Yaariv, 2011), trade and financial markets (Eliott, Golub and Jackson, 2013), R&D collaborations (Goyal and Moraga Gonzales, 2001), friendship and peer effects identification (Currarini, Jackson and Pin, 2009, 2010), to the adoption of health related behaviours (Christakis and Fowler, 2002).

Network theory is particularly well-suited to analysing problems where social distance affects the nature and extent of economic interactions. In a network, agents interact only with a subset of other agents called the neighbours. For instance, in labour markets, information on job vacancies mainly flows along social ties. Likewise, our behaviour and habits are affected by those of our friends, relatives and colleagues with whom we interact and imitate, and whose actions have an impact on our welfare. It is exactly this local nature of interaction that distinguishes network models from models based on coalitional relations. More precisely, while in economic coalitions all members interact with all other members of the coalition, within a network agents may entertain relations which are not transitive, in the sense that A having a tie with B and B with C does not imply that A and C are tied.

Research in network economics has addressed two distinct, though strictly related, issues: (i) how network structures affect the behaviour of social and economic actors; (ii) what incentives agents face in forming the network by means of link creation and deletion (which in turn begs the question how these incentives relate to social incentives, and how efficient are the resulting architectures). Investigation of the above issues has shown that the network structure of career advice can generate unemployment patterns that match the observed correlation and persistence of unemployment much better than classical models do. Furthermore, we have learn that the effect of changing the topology of a social network crucially depends on the strategic features of social interaction (i.e. whether they are substitutes or complements); and that the ethnic biases in the way students form friendships originates both from institutional constraints and from preferences that are not race-blind but favour one’s own ethnic group.

Local interactions and network structures appear to be a prominent feature of many environmental problems. Without having the ambition to be exhaustive, this paper nonetheless considers a wide range of issues and potential areas of application, including: (i) the role of relational networks in the pattern of adoption and the speed of diffusion of green technologies; (ii) common pool resource problems characterized by a multiplicity of sources and users interlinked by an extraction network; (iii) the role of social networks in multi-level environmental governance; (iv) infrastructural networks in the access to and use of natural resources such as oil and natural gas; (v) the use of networks to describe the internal structure of inter-country relations in international agreements, and how this affects the stability of cooperation; and (vi) the formation of bilateral “links” in the process of building up an environmental coalition.

For each of these areas, we examine why and how network economics would be an effective conceptual and analytical tool, and discuss the main insights that we can foresee. We do this by reviewing relevant yet still limited contributions within this emerging research field, discussing new frameworks of analysis, and identifying open issues and questions for future research.

The paper is organised as follows. Section 2 introduces the basic elements needed to define and describe networks, and presents some of the key indices that are used to capture the structural features of a network and to compare different architectures. Section 3 discusses how the network is likely to affect agents’ actions, behaviours and welfare; and what forces/incentives are behind the process of network formation. In section 4 we seek to map the linkages between network economics and the environment by focusing on specific environmental issues and analysing in greater detail how the use of networks can provide new insights for both theory and practice. Section 5 concludes.

2 NETWORK ECONOMICS: KEY FEATURES AND CONCEPTS

2.1 DEFINITIONS

Networks

We define a network starting from a set *N* of nodes. In applications, nodes usually represent socio economic agents, such as firms, consumers, countries, etc… A network *g* can be defined as a subset of the set of all pairs of elements in *N*: $g \subseteq \{ij: i \in N, j \in N\}$. When the order of pairs matters, we say the network is *directed*, otherwise we say that the network is *undirected* (that is, in an undirected network $ij \in g \longrightarrow ji \in g$). A pair $ij \in g$ is called a *link* or a *tie*. More in general, links can carry an associated real number that is usually interpreted as the strength of the link. In most economic applications, however, such weights are set to either 1 (the link is there) or 0 (the links is absent), and g is a non-weighted network. We will denote by $g - ij$ the network obtained by deleting the link ij from g, and by $g + ij$ the network obtained by adding the link ij to g.

An alternative way to represent a network is by means of the *adjacency* matrix *G,* whose generic entry g_{ij} measures the strength of the link between nodes *i* and *j* in *g*. When the network is undirected, the adjacency matrix is symmetric; when links are not weighted, the matrix only contains zeros and ones. The generic element g_{ij}^{m} of the $m-th$ power of the matrix *G* counts how many paths of length m are present in g between i and j.

The *neighbourhood* of node i in the non-weighted network g is the set of nodes that are linked to i in g. The number of such nodes – called the *neighbours* of i – is called the *degree* of i in g. If all nodes are linked to all other nodes we have the *complete network*. Notable architectures include (i) minimally connected networks (*trees*); (ii) *regular networks*, where all nodes have the same degree (a special case is the circle, where all nodes have two neighbours); and (iii) *core-periphery architectures*, which are networks where a subset of nodes – the core – is linked to all nodes in the network and the rest of the nodes are only linked to nodes in the core (a special case is the *star*, where the core includes a single node). See figure 1.

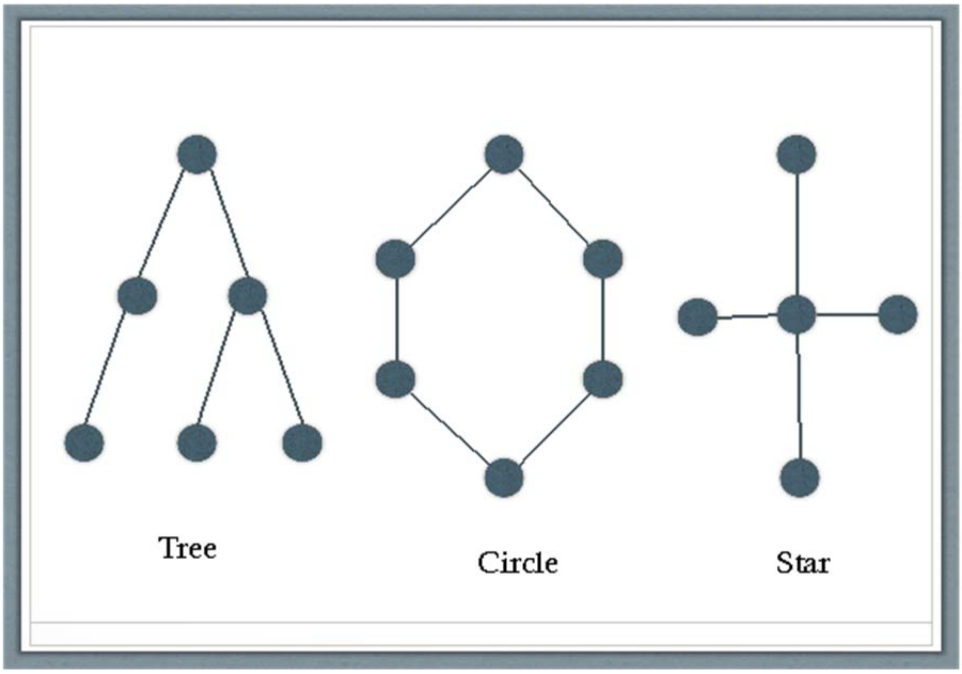

Figure 1 Example of network architectures

Paths and Connectedness

A walk in the network g is a sequence of adjacent links in g. Formally, a walk is a sequence $\{i_0 i_1, i_1 i_2 \dots, i_{m-1} i_m\}$ such that $i_{p-1} i_p \in g$ for all $p = 1, \dots, m$. When such walk exists, we say that the two nodes i_0, i_m are connected in g. A walk such that $i_0 = i_m$ is called a cycle. When the walk never goes twice through the same node we have a *path*. When there are several paths connecting nodes $i_0 \; and \; i_m$, we consider the shortest of these paths to define the *geodesic distance* between $i_0 \; and \; i_m$ as the number of links in this shortest path. We say that the network g is connected if for each pair of nodes there exists a connecting path.

Sub-networks and Components

A sub-network $h \subset g$ is a network with set of nodes $S \subseteq N$ and such that $ij \in h \longrightarrow ij \in g$. For any subset $S \subset N$ we define the restriction of g to S as the sub-network with set of nodes S and with the links that in g only involve nodes in S. The restriction of g to S is denoted by $g|_S$. We say that the subset of nodes $S \subset N$ is connected in g if $g|_S$ is connected. The maximal connected sub-network of g is called a component of g. By definition, a component h of g is such that no link is present in g between nodes in the component and nodes outside the component.

2.2 REPRESENTING NETWORKS

Networks are mathematically complex structures. We can capture some basic structural properties and compare different networks by looking at simple indices, whose qualitative features are briefly described below.

Connectivity

One first measure of network connectivity is the *average degree* which tells us on average how many neighbours nodes have. A different type of information is given by the *diameter* of a network, which is the maximal geodesic distance between any two nodes. If for instance, the diameter of g is 6, it means that it takes at most 6 steps to go from any node to any other node in the network. Another related index, the *average distance*, measures how distant nodes are on average.

Clustering

Within a network, two neighbours of a given node may or may not be themselves neighbours. When they are, they “close” the triangle of relationships by forming a “cluster”. The degree of clustering may greatly vary across networks, depending on the nature of the relations described by links. In a hierarchical organization, for instance, clustering is very low, while in friendships clustering may tend to be quite high, since common friends often tend to become friends themselves. A measure of how clustered a network is looks at all the potential triangles in the networks (a node with two neighbours) and counts the fraction of times that such triangles are actually closed; a slightly different measures takes this fraction for each node in the network, and then averages across all nodes.

Centrality

Nodes in a network may have different degrees of “importance” in connecting other nodes. For instance, a node may be critical in the sense that by removing it from the network, the other nodes would split into two or more components. Or a node may be important because many of the shortest paths that connect the other nodes pass through that single node. Or, still, because it is very close to all other nodes in the network, or to the most important nodes in the network.

Centrality indices have the scope to formally quantify the importance of nodes in the network. A first basic way to think of centrality is to simply consider how many connections a node has – that is, taking a node's degree (possibly normalized by the total number of nodes is one wishes to compare centrality in different network) as an index of centrality. Other notions of centrality make use of more global information about the position of nodes in the network. *Closeness centrality* measures how close a node is to all other nodes in the network, and is given by the inverse of the sum of a node's distances from all other nodes. *Betweeness centrality* measures how important is a node in efficiently connecting other nodes in the network; for a given node i this index is given by the fraction of shortest paths between any two nodes *k* and *j* that go through node i. *Eigenvalue centrality* accounts for the type of connections that a node has in the network; it is based on the (recursive) idea that central nodes are those connected to other central nodes. Finally, Bonachich Centrality counts all walks that depart from a given node in the network, discounting longer walk by an exponential factor.

A suggestive illustration of centrality is given in figure 2 – taken from Jackson (2010) – showing the network of marriages in Renaissance Florence. The Medici family is shown to occupy a very central position, which has been advocated by some historians as one of the key elements explaining their surge to political and social power.

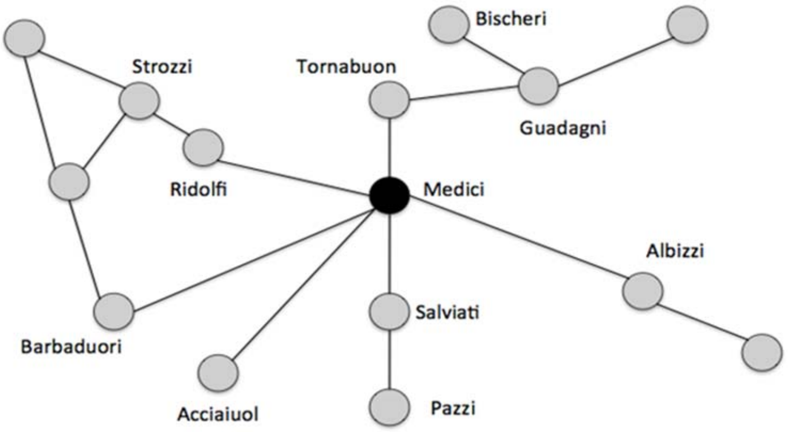

Figure 2 Florentine marriages network. Source: Padgett and Ansell (1993)

Degree Distributions

While centrality describes features of single nodes as a function of the whole network, other measures aim at capturing features of the overall distribution of links in the network. The *degree distribution* of a network provides information about the fraction of nodes that have any given degree in the network. Mathematically, it associates with each possible degree *d* (from 0 to *n - 1*, where *n* is the total number of nodes) the fraction of nodes with degree *d* in the network under consideration. It must be noted that although the degree distribution provides useful information on how evenly distributed connections are in a network (whether, for instance, the network has a considerable fraction of nodes that act as hubs and of nodes that are poorly connected or, alternatively, all nodes have more or less the same degree), this measure is silent about other characteristics such as clustering. Figure 3a gives an example of two networks with the same degree distribution (degenerate, with all agents having degree of 2), but quite different architectures in terms of connectivity and clustering.

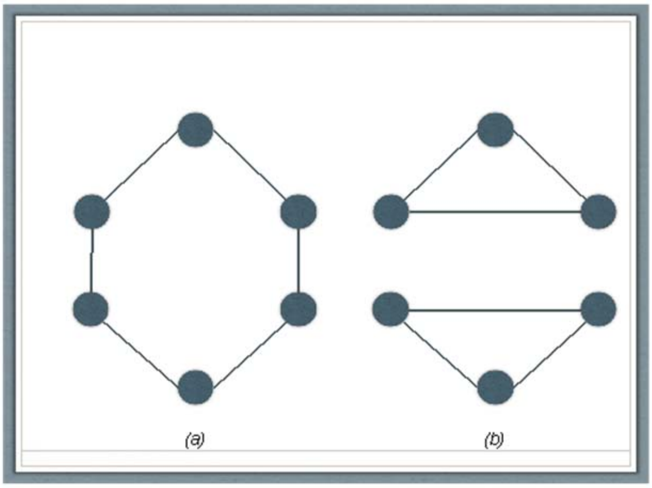

Figure 3a Clustering and degree distribution

Notable degree distributions are (i) the *Poisson distribution*, approximating the expected degree distribution in a purely random network where each link forms with the same given exogenous probability, and (ii) the *scale free* (or power law) distribution, which exhibits fatter lower and upper tails compared to the Poisson, and is generated by models of growing random network where more connected nodes face better chances to form further links with newly born nodes (as in the preferential attachment model by Barabasi et al., 1999)). The fraction of agents with degree *d* is given by $P(d) = cd^{-\gamma}$.

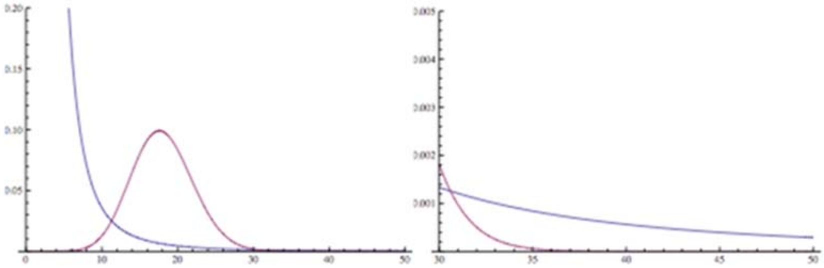

Figure 3b Poisson and scale free degree distributions (upper tail detail in right panel). Average degree = 8, $c = 18, \gamma = 3$.

2.3 WELFARE, BEHAVIOUR AND NETWORK FORMATION

2.3.1 Network Games, Allocation Rules and Efficient Networks

The patterns of social interaction are likely to affect agents' behaviour, aggregate welfare and welfare distribution. The traditional models of game theory have been extended to encompass the structure of local interaction described by the network. In *graphical games*, agents are assumed to only interact with their neighbours in the network, whose actions directly enter their payoff function (compared with traditional game theoretic models where every agents interacts with everyone else). However, feedbacks are present also between agents who are only indirectly connected in the network, and each agent's equilibrium behaviour ends up depending on the entire architecture rather than only on her neighbourhood. Two broad classes of graphical games are: (i) games with *strategic complements*, where an agent's incentives to act increase with the number (or the share) of neighbours taking the action; (ii) games with *strategic substitutes*, where incentives to act decrease with the number (or share) of neighbours taking the action. Strategic complements well describe settings where conformism, imitation or other economic mechanisms correlate agents' behaviour with their neighbours'; substitutes represent problems where incentives to free ride are present, and agents substitute their own (costly) action with their neighbours'.

In large networks, agents may have limited knowledge of the overall architecture beyond their neighbourhood. The class of *network games*, studied in Galeotti et al. (2007), captures this incomplete information aspect by assuming that only the overall degree distribution of the network is common knowledge, and each agent privately knows her own degree, and formulates expectations about her neighbours' degrees and behaviour. Within this framework, it is possible to draw sharp conclusions about the implications of changes in the network's topology on agents' behaviour in the classes of games with strategic complements and substitutes.

Using a reduced form approach in line with the cooperative games tradition, we can associate with each network g a value function v expressing the total welfare generated by agents in the network. The real number $v(g)$ can be thought as the sum of agents payoffs in a game played on g, or as the social "pie" that is generated in g and that must be distributed among agents. Individual payoffs, whether they come from non cooperative equilibrium behaviour or from a centralized mechanism inducing interpersonal transfers of various types, are represented by an allocation rule $a(v,g)$, a vector-valued function mapping each economic problem (a pair v,g) into a distribution of the value $v(g)$. A network g^* is said to be *efficient* with respect to v if it maximizes the size of the pie to be distributed: $g^* = argmax_g v(g)$.

2.3.2 Link Formation, Stability and Efficiency

The way in which the allocation rule $a(v,g)$ shares the total pie among agents determines agents' incentives to form and sever links. For instance, agent i (node i) in network g will have an incentive to form the link $ij \notin g$ if her payoff, as determined by the rule $a(v,g)$, would increase in $g + ij$ compared to g. Any notion of stability of a network refers to such incentives, and is therefore defined with respect to the pair (v,a). Depending on agents' strategic possibilities to revise their links we obtain various notions of stability.

One first important issue is whether agents can form links without the consent of their perspective partners. This modelling choice clearly depends on the specific economic problem one has in mind, and in particular on whether links are directed or undirected. If links represent literature citations or Internet page referrals, unilateral link formation is an appropriate assumption. Mutual consent is instead required in friendships, information sharing, insurance, market agreements, co-authorship, and in many other socio-economic applications.

A second issue is the extent to which agents are able to coordinate their decision to revise links. When links can be formed unilaterally, stability can be defined by directly applying the Nash equilibrium to a suitably defined link formation game. Coordination is instead a crucial issue when mutual consent is required to form a link, since individual actions are not capable of adding links to a network. The notion of *pairwise stability* (Jackson and Wolisnky 1996) assumes that agents can coordinate to form a profitable link: a stable network obtains when no pair of agents wishes to form a new link, and no agent wishes to (unilaterally) sever an existing link. Note that pairwise stability cannot be derived as the Nash equilibrium of a suitable defined link formation game, since: (i) agents can only sever one of their existing links, and (ii) pairs of agents can jointly deviate from a network by forming a new link. The notion of *Nash-pairwise stability,* allowing both the coordinated objection of pairs of agents and the severance of any number of an agent's own connections, is instead a refinement of the Nash equilibrium. The even more demanding notion of *strong stability* (Jackson and van den Noweland 2000), assumes that any subset of agents can coordinate in the joint revision of their links, and possesses similar features to the strong Nash equilibrium of games in strategic form.

Since an agent's decisions to add or sever links potentially affect all other agents in the network (the so called *network externalities*), decentralized linking decisions are likely to lead to inefficient networks from a social point of view. Jackson and Wolinsky (1996) have shown that network formation suffers indeed from a general tension between stability and efficiency. They show that no allocation rule $a(v, g)$ that satisfies natural symmetry and anonymity properties guarantees that the efficient network will be pairwise stable. Given the limited amount of coordination required by the pairwise stability notion, this result highlights a serious inconsistency between private and social incentives in network formation. Other contributions have proposed ways to overcome this tension, focusing on either mechanism design approaches (Dutta and Mututswami, 2000), or on Coase-like bargaining procedures (Currarini and Morelli, 2000), or still on general transfers schemes (Bloch and Jackson, 2007). When spillovers are present across components (a relevant case for environmental problems, where agents benefits and suffer from action taken by other disconnected agents), efficiency generally requires the use of contingent transfers that subsidize the formation or the deletion of those links that are responsible for the spillovers (see Bloch and Jackson, 2007).

3 MAPPING THE LINKAGES BETWEEN NETWORK ECONOMICS AND THE ENVIRONMENT

3.1 DIFFUSION ON NETWORKS: ADOPTION OF GREEN TECHNOLOGIES AND BEHAVIOUR

Much like behaviours, technologies diffuse through social interactions, since adoption by one agent (whether an individual, a firm or a country) increases the likelihood that others will become aware of its existence and potential benefits over the incumbent technology. A wealth of studies, ranging from sociology to engineering has either modelled or lent empirical support to the idea that mutually reinforcing choices lead to accelerating diffusion of a behavioural trait or technology once a critical threshold has been reached. This process is due to slow down by virtue of saturation, once the pool of adopters is so large that there is little scope for imitation, so that the adoption curve asymptotes as depicted in figure 4.

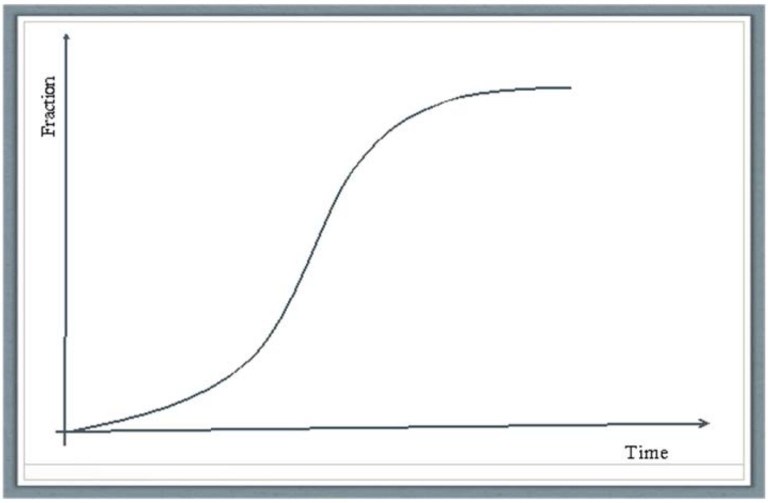

Figure 4 An example of S-shaped diffusion curve

Depending on the context, many definitions have been given to the idea that other people's actions can reinforce one's own choices: 'bandwagon effects' in fashion-oriented behaviour (Leibenstein, 1950), individuals' adoption thresholds (Granovetter, 1978), entrapment (Dixit 2003), network externalities, social reinforcement, cascades (Watts, 2002), tipping (Gladwell, 2000) and "positive feedback trading" in finance (Barberis and Shleifer, 2003), among others. What is common to these theories is the notion that diffusion/adoption of an innovation behaves like epidemics, consistently with the dynamics of figure 4. That is, agents have an adoption threshold that is a positive function of the number of other adopters; an early formalisation of this idea is the Bass model (Bass, 1969).

What about green technology adoption, specifically? In a paper focussed on establishing whether a tipping point exists for the adoption of climate policies by the international community, Heal and Kunreuther (2012) offer illustrative evidence on the role of early adopters (i.e. those located at the left x-axis corner in figure 4) in triggering a global shift from damaging pollutants usage to greener alternatives. The first one concerns the adoption of unleaded gasoline in replacement of leaded gasoline; here the unilateral adoption by the United States meant that the subsequent adoption costs for other countries was confined to modifying refinery capacity, since motor industries exporting to the U.S. had to transition to lead-free fuel immediately after the move. Thanks to these reduced costs for the followers, the new technology spread quickly worldwide. The second example refers to phasing out chlorofluorocarbons (CFCs), a spectacular achievement of the Montreal Protocol on Substances that Deplete the Ozone Layer.[1] In this case, the U.S. decision to sign the

---

[1] As of September 2013, 197 countries have ratified the Protocol, banning the production of chlorofluorocarbons, halons, and other ozone-depleting chemicals.

Montreal Protocol hinged on a technological innovation by Du Pont, the world's largest producer of CFCs, allowing the company to gain from elimination of CFCs. Again, strategic complementary led most countries to phase-out ozone-depleting chemicals.

Empirical work has also established the relevance of the S-shaped curve for the diffusion and adoption of new technologies. Ryan and Gross (1943) and Griliches (1957) demonstrated that the adoption of hybrid corn seeds among Iowa farmers follow the pattern presented in figure 4. More recently, Weir and Knight (2004) find a significant role of schooling, mediated by social networks, in the adoption and diffusion of innovations using data from Ethiopia. Specifically, they suggest that literate farmers are early adopters of new farming practices as well as quick at imitating innovations by others, while illiterate farmers tend to be second-movers and eventually adopt the practices of the innovators. Other studies have looked at the spread of financing techniques. For example, Banerjee et al. (2013) study how participation in a microfinance program diffuses through social networks in several rural villages in South India.

3.1.1 Networks and the Diffusion of Green Technologies

Much of the theory cited in this section, while insightful about the non-linearity of diffusion dynamics, is silent about the topology and the role of the network. This, however, is relevant for the above empirical studies and Environmental Economics more broadly. Even more so when, over space and time, both the rate of innovation and the rate of imitation are likely to vary, in contrast to the constant rates assumed in the Bass model (1969). A theory that aims at investigating the patterns of early adoption/quick imitation by certain groups of farmers relative to others (c.f. Weir and Knight, 2004), will need to allow for heterogeneity both in these rates and in the structure of social relations.

To appreciate the role of the network, one needs to consider that the incentives to innovate and adopt may be affected by peer and neighbourhood effects, which can drastically change the way innovations diffuse relative to a model where individuals update their adoption decision based on the overall frequency of adopters. Jackson (2010, p. 257) notes that '[…] interactive considerations require game-theoretic reasoning, adapted and extended to a network setting.' As an example of the complex link between neighbourhood composition and behaviour, he refers to the choice of software: if one wants it to be compatible with most neighbours, the ensuing interactions must be treated as a coordination game, where adoption by a critical number of neighbours can tip the system to a different technology.

What is important here is the fact that the speed and the extent of diffusion are intimately related to the network topology. A vast literature on diffusion and contagion in social networks has enriched the Bass model by explicitly modelling the component structure of a network. As an illustration, consider the SIS (Susceptible-Infected-

Susceptible) model of infection diffusion, in which agents are born healthy, get infected with some probability and with some probability recover, after which they become susceptible of infection again. The probability that an agent gets infected is proportional to its degree (number of meetings), to the probability that a neighbour is infected, and to the rate of disease transmission, measuring how infectious the disease is. One can show that both the speed of convergence to a non-zero infection steady state and the overall social extent of the infection depend on the topology of the network (in particular, on its degree distribution), and how this topology relates to the rate of transmission (see Jackson 2010).

More specifically, an increase in average degree caused by a first order stochastic dominance shift in the degree distribution always increases the speed of diffusion and the steady state share of infected agents. This result has a very natural intuition: more connections result in more intense social interaction and in a faster spread of the disease. A more subtle effect obtains as a result of second order stochastic dominance shifts in the degree distribution, that essentially increase the fraction of agents with very small and with very large degrees. An increase in the fraction of little connected agents should slow down diffusion, while more numerous well connected agents should speed it up, resulting in an ambiguous trade-off. The net effect depends on the topology of the network and on how this topology combines with the degree of infectiousness of the disease can be explained as follows. A spread of the degree distribution results in an increase in diffusion when the rate of transmission of the disease is large, and in a decrease when the rate is low. An intuition for this result comes from the non-linear relation between a node’s degree and its probability of infection rate: already high infection rates are little sensitive to increases in a node’s degree, simply because infection rates are bounded above. With large transmission rates, infection rates are high in the system, and the effect of increasing the number of very connected nodes is small and dominated by the effect of increasing the number of little connected nodes. The implicit non linearity in the relationship between degree and the infection rate also implies, for specular arguments, that when the infection is little aggressive a spread in the degree distribution increases the speed of diffusion, as the effect of more nodes with large degree dominates the effect of more nodes with very small degree.

Interestingly, similar insights characterize problems where agents take actions strategically and, as in the diffusion model, the probability of taking an action increases with the share (or number) of neighbours taking that same action. Here, as in SIS model, more connections imply faster diffusion; moreover, a mean preserving spread of the degree distribution implies faster diffusion when the incentives to adopt are very sensitive to the degree of an agent – a similar condition to the one we saw in the SIS model, where the rate of transmission had to be very sensitive to the degree. A notable difference between the strategic model of adoption and the SIS model is that conditions for large scale spread apply to the size of the initial adopters, which has to exceed a given threshold in order for diffusion to kick off.

All this suggests that the process of adoption of new technologies is crucially affected by the topology of social relations, and different topologies may imply very different thresholds and limit behaviour of the system, even if all other fundamentals are the same. In the next subsection we discuss the effect of local interaction in a diffusion problem for a socio-ecological system.

3.1.2 Networks in coupled socio-ecological systems

As an example of the additional insights that modelling networked interactions can bring to the study of behavioural diffusion in environmental problems, consider the evolution of cooperative behaviour in resource harvesting. Tavoni *et al.* (2012) and Lade *et al.* (2013) explored the effectiveness of social sanctioning of resource overuse in promoting sustainable extraction. Two types of agents, norm-following co-operators (C) limiting their resource use to the societal efficient amount, and defectors (D) who extract above the sustainable level, interact in a well-mixed population (i.e. absent a network structure which restricts interactions). Either type, when randomly matched with a fellow user of the shared resource, updates his or her strategy based on utility differences.

$$U_c = \pi_c = \frac{e_c}{E} F - w e_c$$

$$\pi_d = \frac{e_d}{E} F - w e_d$$

$$U_d = \pi_d - \omega(f_c) \frac{\pi_d - \pi_c}{\pi_d}$$

where:

- the extractive efforts for the two types are $e_c < e_d = \mu e_c$ ($\mu > 1$; it follows that $\pi_c < \pi_d$);
- production $F = \gamma E^\alpha R^\beta$ results from the two inputs: resource *R* and mean extractive effort in the population N;
- f_c is the share of C in the population;
- $E = N[f_c e_c + [1 - f_c] e_d]$. w is the opportunity cost of labour;
- $\omega(f_c)$ is a nonlinear ostracism function which only kicks in for a sufficiently large share of co-operators and saturates as $f_c \to 1$, similar to the S-shaped curve in figure 4. Below a certain threshold percentage of co-operators, their community is ineffective in sanctioning norm violators.

Social and resource dynamics are coupled, so that payoffs from harvesting vary depending on the composition of the population f_c: the higher the share of defectors ($\text{the lower } f_c$), the more depleted the resource and the less effective the sanctions.

The population composition evolves according to the replicator dynamics, and the probability that an agent switches its strategy is proportional to the difference between his utility and that of the matched individual.

The results of this a-spatial model, where everyone interacts with everyone else, are displayed in figure 5 for varying degrees of the parameter μ.[2] Three regimes of stationary state of the evolutionary dynamics obtain: (i) the defector equilibrium (when the dynamics tend to the left of the figure and $f_c \rightarrow 0$); (ii) the co-operator equilibrium (on the right hand side of the figure, where $f_c \rightarrow 1$); and (iii) the mixed equilibrium where both C and D coexist.

The thinner lines in figure 5 show corresponding results for a model with local interaction where individuals only observe agents in their neighbourhood, thus allowing to study the influence of network structure on the effectiveness of social sanctions (this is taken from Chung et al., 2013). Here, the effect of the sanctions imposed on a norm violator is assumed to depend exclusively on the fraction of co-operators in the defector's neighbourhood.[3] In a regular network of 50 nodes, the figure considers average degrees of *k*=40 (solid curve), *k* = 20 (dashed curve), *k* = 10 (dotted curve) and *k* = 2 (dash-dotted curve). We observe that as average degree declines, the basin of attraction of the co-operator equilibrium shrinks, paving the way for a 'tragedy of the commons'.

---

[2] The arrows in the figure indicate the direction in which the composition of the population evolves, so that one can determine which equilibrium obtains for a given initial share of co-operators (and level of defection by norm-violators).

[3] This is in contrast to the well-mixed population, where all defectors are subject to the same amount of ostracism.

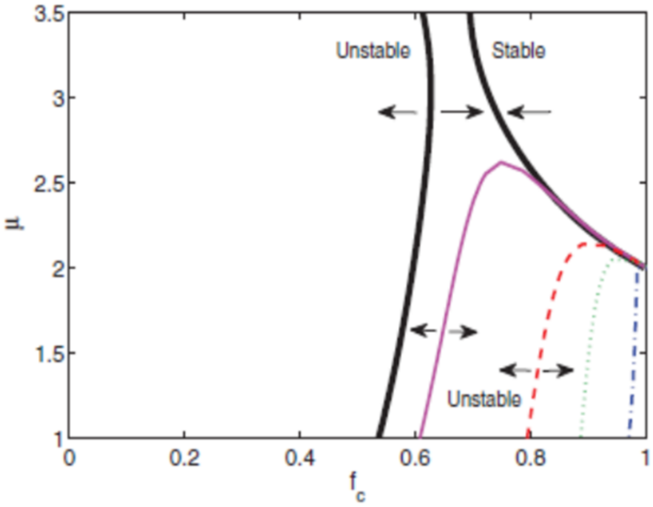

Figure 5 Co-existence of co-operators and defectors in a well-mixed population (thick solid curve) and in regular networks with decreasing average degree. Source: Chung et al., 2013.

This insight stresses the importance of explicitly modelling social interactions within networks: while conclusions from the model where different appropriators interact in a well-mixed population hold true in the case of a complete network (and qualitatively for networks with high average degree), cooperation is destabilised in loosely connected networks.

3.2 ACCESS AND USE OF NATURAL RESOURCES

The access and distribution of natural resources often entails the use of networked infrastructures and markets. This is the case, for instance, of irrigation water and natural gas. In these examples, the cost and benefits from the use of the resource is determined by the pattern of canals and pipelines through which this is sourced and distributed. The efficient use of the resource calls for agreements and contracts between the nodes of the network, whose gains and benefits are determined through complex bargaining processes. The network itself is, to some extent, flexible, as new links can be created and existing links destroyed in pursue of larger profits. The incentives to form or delete a link may well not align with social incentives, as the formation only requires the consent of the two interested nodes, and the deletion often only requires the consent of one of the interested nodes. Due to network externalities, inefficient networks may result from the decentralized formation of links, and a general tension between efficiency and stability has been recognized in early works of network economics (see Jackson and Wolinsky, 1996). Two issues seem to be of prominent interest for the application of network economics to natural resources: how players will share the gains from cooperation through bargaining, and how this will affect, and be affected, by the degree of flexibility of the network and the incentives to form and delete links.

In this section we discuss these issues using, as an illustrative example, the case of the Eurasian natural gas pipelines. Eurasian gas accounts for 40% of EU gas imports, and most of these imports transit through Belarus or Ukraine, both importing gas from the Russian Federation.

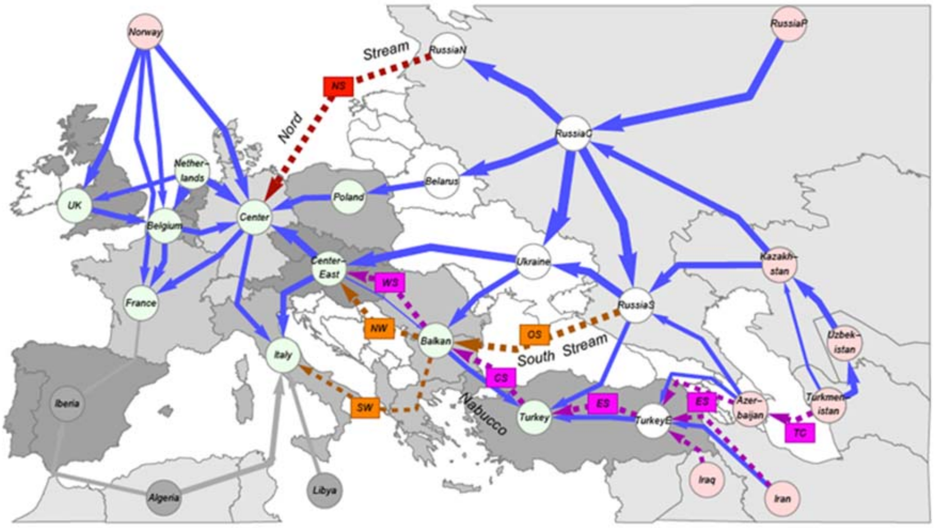

Figure 6 Eurasian pipeline gas network. Source: Hubert and Cobanli

A striking example of the stark consequences of failures in the bargaining process is provided by the 2009 crisis, where the disagreement on gas prices and fees led to interruptions of supply through Ukraine for several weeks (see Hubert and Cobanli, 2012). Such retaliatory behaviour can be viewed as an attempt to build-up bargaining power out of strategic and vital positions in the transmission network. In general, players' bargaining power (and, with it, their final payoff) will depend on their position in the pipeline network, together with other factors such as market size, production capacity and international power. Recent contributions in network theory have provided a framework to study bargaining processes among agents located on a network. These are mainly buyer-seller networks, in which a player bargaining power depends, in a complex manner, on her connections to other nodes on other side of the market, and on the connections of these nodes. However, distribution networks generally have a more complex structure than buyer-seller networks. Specifically, they are characterized by directed links and present strong heterogeneities among players; incorporating these features within a fully-fledged non cooperative bargaining model is a challenging, yet necessary task for future research.

Adopting an alternative approach, based on cooperative game theory, Hubert and Cobanli (2012) have studied the specific problem of Eurasian gas pipelines network. This approach relies on a variation of the Shapely Value for games with a communication structure, that is, games where agents' cooperation possibilities are described by a network. This variant, first proposed by Myerson (1977), is based on a description of coalitional values that take into account the limits to cooperation imposed by the fixed network structure. Using the notation developed in section 2, we let $g|_S$ be the sub-network obtained by only considering nodes in S and those links for which at least one of the involved nodes belongs to S. Let also $C(g|_S)$ be the set of components of $g|_S$, and let $\pi(g|_S)$ be the partition obtained by considering the set of nodes of the components in $C(g|_S)$. Given a primitive characteristic function $v(S)$ describing the payoff possibilities of each coalition S, we can define the new value function $v_g = \sum_{B \in \pi(g|_S)} v(B)$. This function captures the fact that players without links in g are not able to coordinate their actions unless indirectly connected by other players who transmit the necessary information. So, the coalition S is only able to generate a value equal to the sum of values generated by its connected components. The marginal contributions that enter the computation of the Shapley value are, of course, affected by the network. In particular, players who are vital for many connected components, end up having very large marginal contributions and, therefore, a large Shapley value. This, in turns, implies that players who act as connectors in the network will be allocated a relatively large share of the aggregate payoff. Within the context of the Eurasia pipeline network, the resulting allocation rule is such that those countries that, if removed from the network, would impede the flow of gas from sources to users, such as Belarus and Ukraine, have a strong bargaining power.

The outlined relation between the network architecture and players' bargaining power can help interpret recent developments in the (planned) infrastructures of gas distribution. These include: (i) the offshore twin-pipeline *Nord Stream*, which establishes a direct link between Russia and Germany through the Baltic Sea; (ii) the *South Stream* pipeline, providing a direct connection between Russia and Bulgaria, from where gas should flow to Central Europe, Italy and Turkey; and (iii) the *Nabucco* project which should open a corridor through Turkey, thus connecting Europe to new suppliers in the Middle East and the Caspian region. If implemented, these projects would considerably weaken the bargaining position of Belarus and Ukraine, reshaping the power along the network at the advantage of Russia and Europe. In terms of network economics, the very fact that these projects are being planned or undertaken suggest that the current configuration of pipelines does not constitute a “pairwise stable” network architecture (see Jackson and Wolinksy, 1996). This notion of stability would in fact require that no pair of nodes has an incentive to bear the cost of a new link, and that no node find it profitable to cut any of its links. As in the case of the newly planned pipelines, such incentives are determined by the expectation of a new payoff allocation following the creation or deletion of a link. This makes clear that a better understanding of the economics and strategy of networked resources would call for an analysis of network formation, itself based on a careful assessment of incentives to form and sever link, of the associated costs and gains in bargaining power, and of the consequences for the system as a whole. This seems to be a challenging and exciting area for future research.

3.3 COMMON POOL RESOURCE MANAGEMENT AND GOVERNANCE

The collective management of natural resources is increasingly being recognised as a critical dimension of sustainable development and a key determinant of economic performance, especially in the rural sector of developing economies (Platteau, 1991; Balland and Platteau, 1996; Ostrom, 2003; Bardhan et al., 2006). By its nature, collective action involves interdependency among individuals. For example, the maintenance of an irrigation network requires the stabilization of the rims and the desalting of minor channels across farmers' land. In such contexts, the effort of one farmer is likely to influence the activity of other farmers along the network, thus implying strategic interactions among individual users. This interdependency, combined with the non-excludable and rival nature of many natural resources, poses significant challenges and raises the question of whether individuals are capable to coordinate their action and successfully manage resources held in common.

The conventional theory of collective action – centred on the powerful metaphors of the tragedy of the commons (Hardin, 1968), the Prisoner's Dilemma game, and the free-riding problem (Olson, 1965) – offered a pessimistic yet influential answer to this question. Indeed, Hardin's conclusion that the users of a common resource are "locked into a system that compel [them] to increase its use without limit" has for long dominated the way in which social scientists thought about shared resources, and been interpreted as an argument in favour of privatization and central government control (Ostrom et al., 1999).

Over the past decades, significant advancements have been made in the collective action literature and the earlier conventional wisdom is no longer regarded as the only relevant view. Using multiple methods of analysis, scholars from different disciplines and backgrounds have shown that the tragedy of the commons is not inevitable, and individuals have the potentials to act collectively.[4]

Recognition that collective action is possible has, in turn, shifted the attention of more recent research towards the question of why collective action emerges and under which conditions it is more likely to succeed or fail. Within this context, a number of structural variables have been identified as critical for the successful management of common-pool resources. These include institutional arrangements concerning monitoring, sanctions and accountability; group characteristics related to

---

[4] Examples of cooperative behaviour have been identified in a wide range of contexts. These include the management of fisheries (e.g., Acheson, 2003; Singleton, 1999), forests (e.g., Mckean, 1986, 2000; Schoonmaker Freudnberger 1993), pastures (e.g., Gilles et al. 1992; Netting, 1981; Nugent and Sanchez, 1999), and groundwater resources (e.g., Blomquist 1992; Trawick, 2003; Marchiori et al., 2012).

size, levels of wealth, and social capital; and attributes of the resource system, such as well-defined boundaries, unpredictability of resource flows, and resource mobility.

As noted by Agrawal (2001), while the first two sets of variables – i.e. institutional arrangements and group characteristics – have been studied extensively at both theoretical and empirical level, our understanding of factors related to resource characteristics is still relatively limited. Yet the physical complexity of natural resources may have important implications for whether and how users can sustain effective institutions. For example, as water moves through a landscape, hydrological attributes such as quantity, quality, location and timing, are likely to be influenced by land use and vegetation patterns. The interconnected nature of the hydrological cycle, thus, implies that many actors and sectors influence water resources at different geographic scales and administrative levels of governance.

Another aspect that characterises many resource problems yet fled the attention of the literature is the multiplicity of commons. Most models assume that there exists a single source exploited by many users. In fact, the most representative commons (e.g. forests, pastures, and groundwater resources) are local, but numerous. The multiplicity of sources can raise interesting political and economic questions. For example, the severe drought that affected Spain in 2006-2007 led the government to consider the possibility of transferring water from the north to the south through the construction of new pipelines. This proposal gave rise to a political debate about regional and national sovereignty over water resources, and the potential economic and environmental consequences of water transfers.

Advancing our understanding of the socio-ecological complexities associated with common-pool resource management requires the consideration of geographic and social distances, and the analysis of how localised interactions give rise to larger-scale patterns that can both facilitate and hamper collective action. Network economics is particularly suited for this purpose, and can help to systematically analyse the structural characteristics underpinning many common-pool resource problems.

3.3.1 Networks of commons

A first important step towards the analysis of common-pool resource problems with multiple sources was recently made by İlkiliç (2011). In this paper, the author considers a situation in which n (water) sources $s_1, s_2, \dots, s_n$ and m cities $c_1, c_2, \dots, c_m$ are embedded in a network that links cities with sources. Figure 7 provides an example of possible network structures in the case of two cities and two sources. The first graph, describes a complete network where each user is linked with both sources, while in the second graph, c_2 is connected only to s_2.

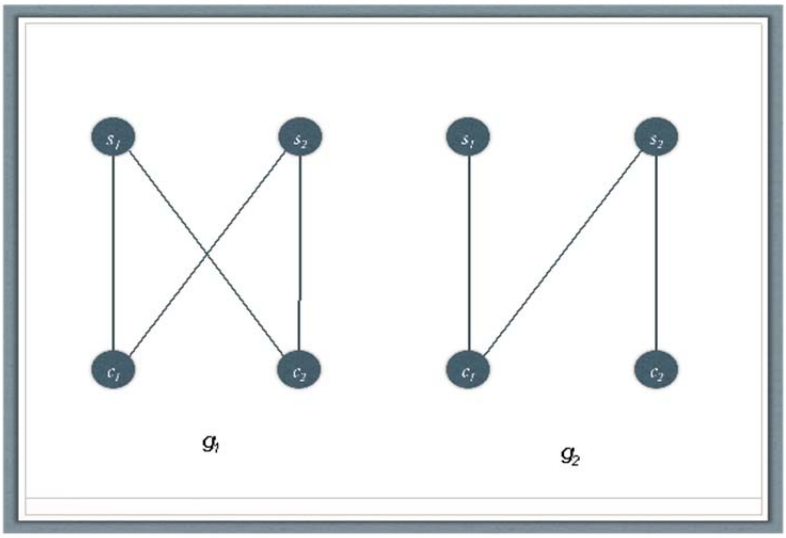

Figure 7 Two different networks of two cities and two sources

The cities receive a value from consumption of the resource, but extraction is costly. The benefits associated with water consumption are assumed to be a concave function of the total extraction made by the city; the cost of extraction from a given source is a convex function of the total extractions from that source. Specifically, city j's utility takes the following form:

$$u_j(Q_g) = q_j - \frac{q_j^2}{2} - \sum_{s_i \in N_g(c_j)} q_{ij} q_i .$$

where q_{ij} is the amount of water extracted by city c_j from source s_i, q_j is the total amount extracted by c_j, and q_i is the total amount extracted from source s_i. Note that each city's extraction from a given source has a negative cost externality on all other users of that same source.

Within this setting, the paper first analyses the non-cooperative extraction game where users freely decide how much to extract from each source they are connected to, and then characterises the efficient use of sources. In the extraction game, a city's exploitation of a given source turns out to be proportional to the Bonacich centrality of the link connecting the city to that source.[5] Consider, for instance, the two cities-two sources case of figure 7. It can be shown that, if the network structure is as in graph g_1, the link flows at equilibrium are $q_{11}^* = q_{21}^* = q_{12}^* = q_{22}^* = 0.2$. Furthermore, and consistent with intuition, these are equivalent to the equilibrium extraction levels in the

---

[5] Note that while in the traditional model of games on networks, where each node is a player, equilibrium behaviour relates to the Bonacich centrality of nodes (see Ballester et al., 2006), here the equilibrium relates to the Bonacich centrality of links. This is due to the fact that the city-to-source network is bipartite and only the nodes in one of the two independent sets (the cities) are strategic players.

case of a single common source. That is, a complete network adds no complexity to the standard problem of commons. By contrast, if the network is incomplete as in g_2, the extraction levels at equilibrium are $q_{11}^* = 0.2857$, $q_{21}^* = 0.1429$, and $q_{22}^* = 0.2857$. In this case, c_2 – which is now connected only to s_2 – exploits this source more than in the complete network. This, in turn, makes the extractions from s_2 more costly, leading c_1 to consume less water from this source and rely relatively more on her exclusive connection s_1. Hence the absent link between c_2 and s_1 harms both c_2 (which is lacking the link) and c_1 (the city she shares the source with c_2).

More generally, in a common-pool resource game with multiple sources, a user's extraction at a source does not only depend on the number of users it shares it with. It also depends on the number of sources that these other users are linked to; and on the number of users that sources are linked to, and so on. That is, the externalities diffuse through the network ad infinitum.

From a policy perspective, the analysis suggests that disregarding the structure of the network may be misleading because different structures affect both overall extraction levels and the distribution of the resource across users and sources. Going back to the previous example, the complete network g_1 leads to relatively higher overall water consumption. However, the incomplete structure g_2 is such that s_2 is exploited more severely. This, in turn, may have implications for both the urgency and type of intervention depending on how close to the point of non-recovery is the resource as a whole, and on the ecological and socio-economic importance of different sources within the network.

The topology of the network also matters for the efficient use of the various sources. First, the paper shows that all efficient allocations are characterized by the same aggregate extractions source by source and city by city. More importantly, it turns out that the efficient used of water in a given network is equivalent to the efficient use that would result by partitioning cities and sources into independent "regions". Each region would comprise a subset of cities together with the sources to which these cities have access in the network, and within each region the aggregate water use from each source would be the same as if the region was internally fully connected. This conclusion seems to support a management approach based on the creation of distinct and independent areas of water exploitation, where subsets of cities have exclusive access to a subset of sources.

A number of salient issues seem to deserve further investigation within this framework. In particular: (i) What networks are socially efficient in a world where links are costly? (ii) What are the incentives of individual cities to form links to sources? And are individual incentives to form and sever links aligned with social ones, as in other network-based allocation problems, such as in Kranton and Minehart (2001); (iii) How would the predictions change if sources were linked to one another (think, for example, of the complex connections between groundwater and surface water); (iv) What is the effect of considering heterogeneous cities and sources?

3.3.2 Multi-level governance in the water sector

As previously mentioned, the governance of water resources is an inherently complex process due to both the interconnectedness of the hydrological cycle and the many actors and sectors that affect water resources at multiple scales.

Responses to water problems are often too narrow and largely based on top-down centralised approaches, which are generally poorly suited to deal with the socio-political and ecological complexities that underpin water use and management (Pretty and Ward, 2001; Molle et al, 2007). At the same time, new frameworks for governing water have started to emerge, which see national governments increasingly devolving decision-making responsibility to local authorities and encouraging stakeholders' participation. The underlying rationale is that involving actors at different scales can lead to improved accountability of stakeholders, higher legitimacy of the decisions, and management strategies that are better adapted to local conditions (e.g. Marchiori et al., 2012).

These ideas are captured in the concepts of co-management, multi-level governance, and decentralization which have emerged and been widely applied in the environmental policy literature. Researchers within these fields distinguish between a 'vertical' and a 'horizontal' dimension of governance, where the former refers to the linkages between higher and lower levels of government, including their institutional, financial, and informational aspects; while the latter refers to cooperative arrangements between a range of public and private actors in the formulation and adoption of development strategies.

In the field of environmental economics, on the other hand, game theory and bargaining theory have provided a valuable framework for studying the strategic incentives of individual decision-makers, the features of the bargaining process, and the properties of negotiated solutions to water allocation and management problems (see for a review Carraro et al. 2007). This strand of literature has significantly advanced our understanding of the potential of participatory approaches, and helped to identify the challenges associated with their implementation in practice. However, bargaining models generally neglect the structural pattern of relations between individuals, organisations and other social actors that influence water resources at different scales. As shown by recent research, the *topology* of social networks may have a significant impact on how actors actually behave and their abilities to sustain cooperative governance arrangements (Bodin et al., 2006; Newman and Dale, 2005; Wasserman and Faust, 1994). By explicitly modelling the structure of social and economic relations, network analysis can usefully complement existing approaches and help to tease apart how localised interactions give rise to larger-scale patterns that can both enhance or hinder water governance initiatives.

Using a network approach to investigate how activities connected to water are governed entails, first of all, identify all the actors that directly and indirectly influence the complex of water resources, and map their formal and informal relations. Direct influence means that an actor directly modifies water flows through withdrawals and discharge activities, flow control measures and land use. Other actors may exert an indirect influence by affecting the activities of those who use water directly. Think, for example, of a governmental body that provides funding for the construction of a new irrigation scheme. The relational ties between actors may be of different nature and involve funding, information and knowledge exchange, and collaboration (e.g. in water maintenance activities). Figure 8 provides a stylised representation of a multi-level governance network of actors operating at different scales and affecting water flows through different activities.[6]

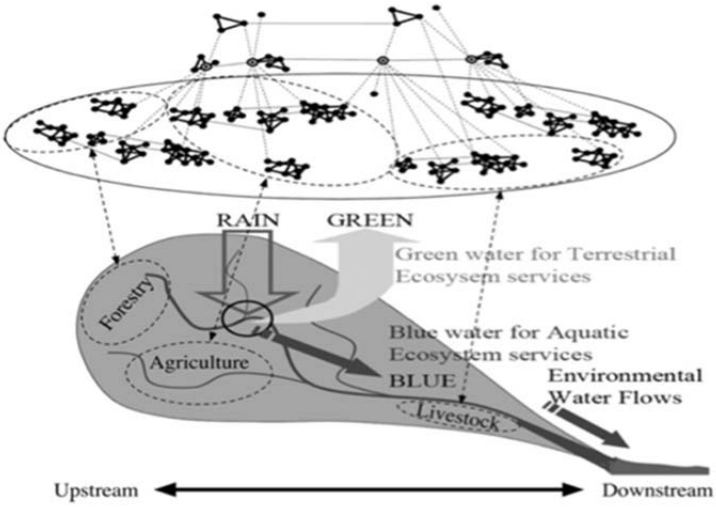

Figure 8 A network of actors operating at different scales and interacting with the complex of green and blue water sources and flows. Source: Ernstson et al. (2010)

---

[6] Figure 8 includes both ‘blue’ and ‘green’ water sources. The former consists of freshwater in rivers, lakes and aquifers; the latter refers to the precipitation on land that does not run off or recharge the aquifers, but is stored in the soil and sustains plant growth. An integrated approach to water management should include both since hydrological attributes such as quantity, quality, location and timing are all influenced by land use and vegetation patterns (ADD REF).

To date, empirical research applying quantitative network analysis to natural resource governance is still very limited. Yet, some valuable insights and hypotheses have started to emerge in this evolving field. One such hypothesis is that the higher the *network density* (i.e., the number of existing ties divided by the number of possible ties), the more potential for collective action and other kind of collaborations that would help actors avoid conflicts and develop effective management strategies. Several studies in the natural resource governance literature support this hypothesis. In the context of rural Kenya, for example, King (2000) showed that fishermen communities characterised by a higher number of interactions among themselves and with government officials were relatively better able to deal with a series of unfavourable developments related to the fishery. Similar results emerge from Conley and Udry (2001)'s analysis of agricultural practices in Ghana, where high network density is associated with the development of new technologies and the diffusion of more sustainable management practices. As noted by Bodin and Crona (2009), however, some caution is warranted since there is also evidence that the positive effect of network density in natural resource governance is not necessarily monotonically increasing. Indeed, very high tie density can lead to homogenization of information and knowledge, which results in less efficient resource use and reduced capacity to adapt to changing conditions.

Other structural characteristics affecting governance processes and outcomes include the level of *network cohesion* and the degree of *subgroup connectivity*. Broadly speaking, network cohesion refers to 'the extent to which a network "hangs together" instead of being divided into separate subgroups' (Bodin and Crona, 2009) – see figure 9, graphs (a) and (b). When several clearly distinct subgroups are present, the density of relational ties between groups can be regarded as low. Relating this to the above discussion of the (mostly) positive effect of network density on collaborative processes, one can conclude that less cohesive networks may hinder the emergence of integrated governance initiatives. However, the formation of subgroups may also have implications for a process deemed important for natural resource governance, namely the generation of specialised knowledge (e.g. local ecological knowledge). The extent to which the development of specialised knowledge is of use in governing complex ecosystems, in turn, depends on whether stakeholders are able/willing to transfer such knowledge across subgroups (i.e. on the degree of subgroup connectivity). Hence, network analysis can help find the right balance between an overall structural cohesion on the one hand, and allowing for the presence of multiple subgroups on the other.

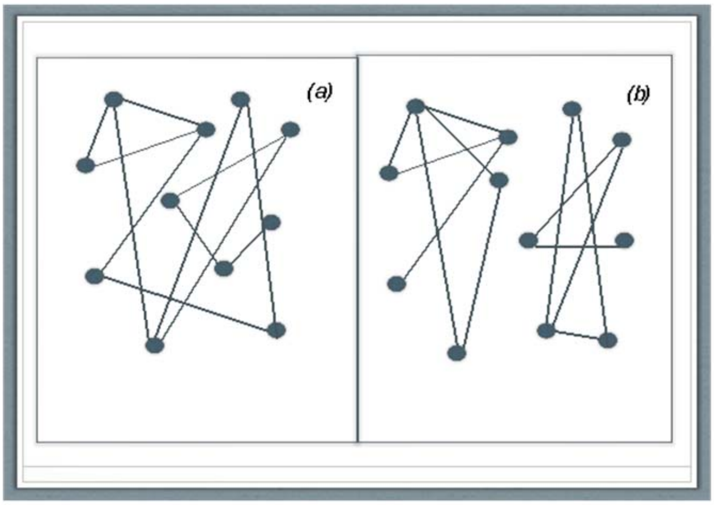

Figure 9 Graph (a) represents a network without any clearly distinguishable subgroups (high cohesiveness), while (b) depicts a network characterised by two isolated subgroups (low overall cohesiver

In addition to features of the network as a whole, it may be important to assess structural characteristics at the level of individual actors (i.e. the nodes of the network). For example, by occupying certain central positions in a social network, some actors may be able to critically influence other relevant stakeholders, thus favouring (or blocking) the development of sustainable management initiatives. There are various ways of measuring centrality in social networks. Two of the most commonly used measures are *degree centrality* and *betweenness centrality*. The former refers to the number of ties an actor possesses; while the latter measures the degree to which an individual actor links other actors who would otherwise be disconnected. These measures are used by Stein et al (2011) to identify key players in the complex social and institutional landscape underpinning water governance in the Mkindo catchment, Tanzania. Within this context, the network of actors that either directly or indirectly influence water flows is a diverse set of players, ranging from local resource users and village leaders to higher-level governmental agencies, universities and NGOs. Results show that village leaders play a brokerage role in the network connecting water and land related activities within their respective village and, to some extent, across villages. The organisations with a formal mandate for the management of water resources, on the other hand, link across larger segments of the catchment, but are not well connected to local communities. From a policy perspective, the analysis suggests that it may be important to integrate village leaders into formal water governance systems, and highlights the need to strengthen vertical links between local communities and governmental bodies operating at the district level.

Reflecting on the above discussion, it is clear that the topology of a social network can significantly influence how actors behave and their abilities to manage water and other natural resources. As we have seen, important differences in governance processes and outcomes can be expected among networks experiencing different degrees of cohesiveness, sub-group connectivity and centralization. Moreover, most structural characteristics do not have a monotonically increasing positive effect, and favouring one characteristic often comes at the expense of another. All this raises a number of interesting issues and questions for future research; for example, what are the 'optimal' level and mix of different network characteristics for the effective governance of natural resources? And how can social networks of resource users develop favourable structural characteristics? In line with Bodin and Crona (2009), we also think that in addition to empirical studies, more theoretical work on the role of networks in natural resource governance is needed. Theoretical models of various behavioural characteristics can help generalise some of the results of the case-study literature, and provide further insights into how different network structures can emerge and evolve over time. Finally, it is important to notice that not only the structure of a network can evolve, but also the content of what is transferred through its links can vary. For example, a link initially used only for the exchange of some specific kind of information can evolve into deeper social interactions, which can facilitate the formation of common norms and values. A network perspective holds great potential in enabling the analysis of such interactions and their direct and indirect effects on governance processes and outcomes.

3.4 NETWORKS, COALITIONS AND INTERNATIONAL AGREEMENTS

In this section we discuss two issues in international cooperation that would benefit from the explicit consideration of networks and from the application of notions developed in network economics. In a nutshell, in section 4.4.1 we discuss new insights on the stability of cooperation that would obtain from the explicit consideration of countries' bilateral relations within a cooperating coalition (here represented by a network). In section 4.4.2 we consider the process of coalition-building through sequential bilateral contacts, and discuss the trade-offs between centralization and delegation of these contacts.

3.4.1 The Internal Structure of Environmental Coalitions

A common, yet restrictive assumption in the economic literature of IEAs is that countries are symmetric. When taken into consideration, asymmetries are typically modelled as differences in terms of costs and benefits of emission abatement. However, due to their history of political, economic and cultural interactions, countries may also differ with respect to their relationship and role within the process of building up cooperation (see Section 4.4.2). Because of these differences, even within a cooperating coalition, certain countries may find it easy to communicate and agree on proposals, while other countries may have little, if any, relations. These differences in bilateral relations within the coalition are likely to characterize countries' relations should the coalition break down and, with it, their possibilities of cooperation after the break up. If, for instance, two countries A and B manage to cooperate within a larger coalition only thanks to the mediation of a third country C, these two countries would probably find it difficult to cooperate if C were to leave the coalition.

To put things more formally, we associate with the environmental coalition S a set of (possibly weighted) bilateral links, expressing, for each pair of countries in S, the strength of their diplomatic, political and economic relationship. In the simplest case, we may think of a {0,1} undirected network, where countries either communicate or not within S. The cornerstone of our analysis is the mechanism described above: by describing countries' bilateral relations, the network predicts countries' cooperation possibilities in case the coalition should break apart. Consider, for instance, country 2 in the left panel of figure 10, mediating all other bilateral relations; 2's defection from the three-country coalition would cause a total breakdown of cooperation, as countries 1 and 3 would not be able (or would face prohibitively high costs) to communicate. If 2 were to defect from a coalition internally structured as in the right panel of figure 10, a smaller cooperating coalition with 1 and 3 as members would be possible.

What matters for our argument is the observation that, in the presence of spillovers, what a country expects to obtain by defecting from a coalition crucially depends on the expected patterns of cooperation after the defection. Free riding incentives are clearly maximal when the remaining countries are expected to stay together and continue to cooperate. This is the so-called "delta" assumption, and leads to the prediction of an endemic instability of cooperation when spillovers are positive (as in the case of environmental agreements). Free riding incentive are, instead, minimized when other countries are expected to stop cooperating altogether after a defection – the "gamma" assumption – in which case global cooperation has been shown to be possible (see Chander and Tulkens, 1999). By specifying the internal structure of a coalition, the network pins down countries' expectations on post-defection scenarios, and therefore their incentives. For instance, the gamma assumption is naturally associated with country 2's defection in network (a) of figure 10, while the delta assumption would appropriately describe expectations after 1's and 3's defections. In general, the defection of a sub-coalition $T \subset S$ would be followed by a partition of the remaining players $N \backslash S$, where each element of the partition corresponds to a component of the sub-network $g|_{N \backslash S}$.

By shaping defectors' incentives, relational networks endow a cooperating coalition with specific stability properties that depend on the sign of coalitional spillovers. In figure 10, for instance, the "star" network of the left panel provides all players with lower incentive to defect under positive spillovers, and with higher incentives under negative spillovers, than the complete network on the right panel. More generally, adding links to a given network always has the effect of lowering incentives to defect under negative spillovers, and of increasing these incentives under positive spillovers. This suggests that minimally connected structures would endow the coalition with strong stability properties under positive spillovers.

Additionally, a very sparse internal structure would also limit the possibilities of coalitional members to coordinate on defections. In the star network of figure 10, for instance, countries 1 and 3 would not be able to coordinate on a joint defection, unless they get player 2 involved. This is not the case in the complete network, where 1 and 3 can autonomously take joint decisions. The effect of the network on coordination was analysed by Demange (2006) in standard cooperative games and by Currarini (2007) in games with spillovers. A basic insight is that, under positive spillovers, sparse networks maximize coalitional stability by both limiting the *number* and the *profitability* of potential defections. Things are more ambiguous under negative spillovers: while sparse networks limit the number of potential defections, they maximize their profitability, resulting in a trade-off that leaves space for intermediate structure with average density.

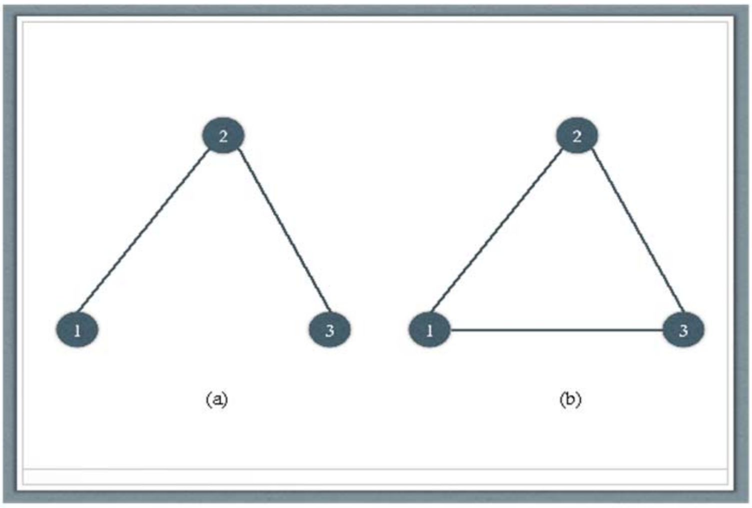

Figure 10 Internal structures of a 3-country coalition

While the above discussion stresses the role of the relational network in shaping players' outside options, there are other ways in which the network is likely to affect players' bargaining power within the coalition. In the left panel of figure 10, while under positive spillovers player 2 has a low outside option due to limited free riding possibilities, he is nevertheless responsible for keeping the coalition united and, therefore, for generating the gains from cooperation. This should increase its bargaining power compared to the complete network (right panel), where 2 is not in such a pivotal position. This is indeed recognized by various allocation rules that take account of the network, such as the Myerson Value, an extension of the Shapley Value to cases where players' cooperation possibilities are described by a network. The main insight here is that while pivotal players enjoy a stronger bargaining position under negative spillovers, a trade-off obtains under positive ones, where pivotal players, who play an essential role within the coalition, end up facing low outside options and, as a result, weaker bargaining power. More research in needed to fully understand the interplay of the different roles of the network in shaping agents bargaining power, and how this interplay affects the stability of environmental coalitions.

3.4.2 Delegation and Centralization in the Build-up of Environmental Coalitions

The traditional approaches to environmental coalitions have either overviewed the process through which coalitions are built (adopting for instance the notion of core of a cooperative game, as in Chander and Tulkens, 1997)), or made use of very stark models of coalition formation, in which one coalition is formed by means of simultaneous announcements of membership (see Carraro, Barret,). However, the process by which environmental coalitions are formed can be varied and multifaceted, and the timing and framing of negotiations is likely to matter for the final success of cooperation. In particular, large coalitions are likely to be built gradually, with a limited number of very committed members as first signatories, who then adopt various strategies to enlarge the coalition.

In many instances of international environmental cooperation, one or more countries have in fact played the role of perpetrators of the process, either because more inclined to solve global environmental problems, or because traditionally playing a leading role in the international arena. Such countries face the task of building up a larger coalition by means of several and successive individual contacts with other perspective members, through complex negotiation processes. The design of such bilateral contacts is a crucial element of cooperation, and attains to the timing of such contacts, their degree of centralization and delegation, the personal involvement and commitment of perpetrators and of perspective members. The perpetrator may, for instance, opt for multiple and simultaneous contacts with most or the other potential members, adopting therefore a centralized procedure of coalition building. Alternatively, it may identify a restricted set of players to contact in a first stage of negotiation, and delegate to these players the task of further enlarging the coalition.

Both centralization and delegation have plausible pros and cons. Advocates of centralization would probably stress the importance of a widespread use of the authority and charisma of the perpetrator, whose central role would be interpreted as signal of its commitment to the cooperation process. Delegation would probably be preferred when diplomatic, geographical and historical relations between countries are very heterogeneous, and the initial perpetrator would lack the necessary information and/or diplomatic strength to successfully negotiate with certain potential new members. In these cases, the perpetrator may better serve the final goal of global cooperation by delegating the creation of new contacts.

The choice between delegation and centralization involves other, less obvious, aspects that are strictly related to the economics of cooperation and to the resulting patterns of strategic interaction. In this section we discuss such aspects, frame them in a stylized example of coalitional externalities, and claim that a general analysis of these issues would greatly benefit from the use of network formation theory and from our knowledge of strategic interdependence in networks.

To fix ideas, consider the following three-player example, developed in full detain in Currarini and Feri (2007). A perpetrator *i* has the task of building up a coalition with other two players, *j* and *k*. The benefits from cooperation are captured by a partition function *v*, mapping each partition of the set of players into a vector of payoffs, specifying an aggregate payoff for each coalition in that partition. Formally, we let *v(S,π)* denote the value generated by *S* in the partition π. In our example, we set $v(\{i\},\{i,j,k\}) = v(\{j\},\{i,j,k\}) = v(\{k\},\{i,j,k\})$ and $v(\{ij\},\{ij,k\}) = v(\{ik\},\{ik,j\}) = v(\{jk\},\{i,jk\})$ by symmetry. We also assume that the grand coalition *{ijk}* is efficient, by this meaning that is generates more aggregate payoff than any other partition of the players' set: $v(\{123\},\{123\}) \geq \sum_{S\in\pi} v(S,\pi), \forall\pi$.

The perpetrator *i* designs the structure of his contacts with *j* and *k*. Either *i* contacts *j* and *k* simultaneously, proposing to form a coalition of three players, or sequentially, contacting *j* first, proposing him to join the forming coalition, and delegating him the task of enlarging the coalition to *k*. In other words, *i* admits j in the coalition, and transfers to *j* the technology to negotiate with *k.* The assumption that the perpetrator can commit not to contact agent *k* when delegating to agent *j* the contracting power is crucial and considerably simplifies the equilibrium analysis and allows us to get a first very sharp intuition. The two scenarios are illustrated in figure 11.

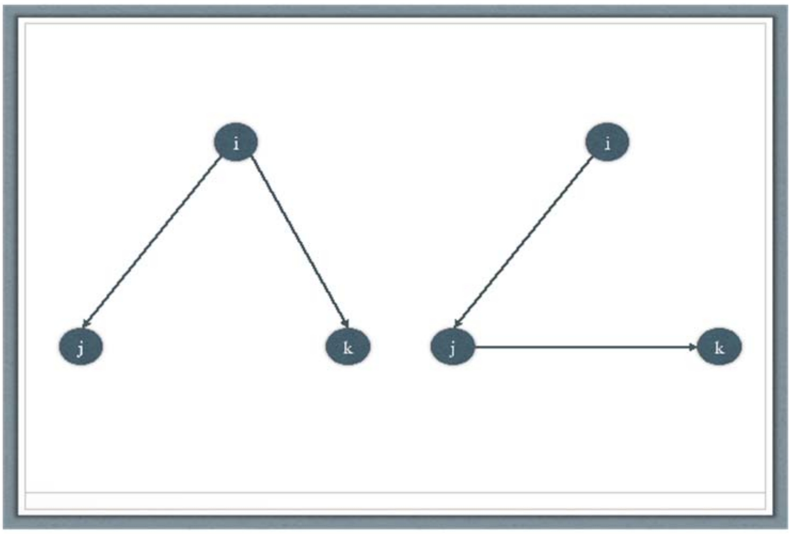

Figure 11 Centralised (left) vs. decentralised (right) contacts.

In the first centralized scenario, *j* and *k* simultaneously receive an offer. For both of them to accept, the offered monetary payoff has to exceed the outside option given that the other has accepted. These outside options are $v(\{j\},\{j,ik\} = v(\{k\},\{k,ij\}$. If the perpetrator delegates, then player *j* needs to receive at least what he would get by rejecting the offer, which is $v(\{j\},\{i,j,k\})$. Player k's payoff when contacted by *j* would instead be at least $v(\{k\},\{ij,k\}$, his outside option if rejecting to join the coalition.

Summing up, the perpetrator needs to give up different slices of the total cake in the two alternative regimes: by centralizing contacts, *i* gives up $v(\{j\},\{j,ik\} + v(\{k\},\{k,ij\}$; by delegating, *i* gives up $v(\{j\},\{j,i,k\}) + v(\{k\},\{k,ij\}$. Which regime is preferred by the perpetrator clearly depends on whether $v(\{j\},\{j,i,k\} > v(\{j\},\{j,ik\}$ or, instead, $v(\{j\},\{j,i,k\} < v(\{j\},\{j,ik\}$. In the terminology of coalitional games, it depends on whether agents face negative or positive coalitional spillovers. In particular, the perpetrator will prefer centralized contacts when spillovers are negative, and sequential contacts when spillovers are positive. Also, when there are intrinsic reasons to centralize contacts (based, as we said, on the perpetrator authority), there is a trade-off between these reasons and the strategic incentives to free ride in a centralized process, and this trade-off may be resolved in favour of delegation the stronger free riding incentives and/or the weaker the perpetrator's authority.

The role of externalities on outside options, bargaining power and the resulting structure of contracts have been stressed in various papers in the contracts literature. Genicot and Ray (1999) suggest that the presence of negative externalities may induce the principal to first contract a subset of players, and then extend contracts to other individual players – a sort of *divide and conquer* strategy. Similar insights are present in Galasso (2007). The main insight here is that the first set of contracts has the purpose of decreasing the outside options of the remaining players, who are then contracted at better conditions for the principal. The reason why a fully centralised structure is not optimal in these papers is that players can coordinate before responding to the principal's offer. Another difference with our stylized example above is that the principal cannot commit to transferring the contracting power to the agents. A similar mechanism underlies the analysis of centralized contracts with externalities by Segal (1999), where is shown that positive externalities may induce the principal to delegate inefficiently low activity levels, in the attempt to lower agents' outside options and retain a larger share of the social surplus. A general setting that extends the three-player example described above to many agents is the sequential "link formation and bargaining" game in

Currarini and Morelli (2000). There, the sequential formation of links has been shown to induce efficiency in the absence of externalities, thus overlooking the free riding incentives and their effects on coalition formation. Also, although in that paper the principal can decide whether to simultaneously offer a link to all agents or to delegate to the second agent in the protocol the task to form further links, the principal cannot retain the exclusive right to propose contract. The centralized contracting situation realizes therefore only if all agents reciprocate the principal's link offer and do not form links among themselves.

4 CONCLUSIONS

Network structures are relevant in many environmental problems, ranging from the diffusion of green technologies, the management of multi-source commons, the networked access to natural resources, to the dynamics of environmental agreements. In this paper we have discussed how network economics can help to model and analyse a variety of these problems, and what new insights can result. Local interaction and network structures seem to bear potential applications in other environmental problems that we have not covered here, including multi-issues environmental negotiations, issue linkage, trans-boundary pollution problems, biodiversity and conservation, peer effects in health related behaviour with externalities (such as smoking), fisheries, risk assessment and others. We hope that the present paper can stimulate research on these topics, both theoretical and applied, explicitly embedding networks in the traditional models of environmental economics. Some of these applications are the subject of our current research.

REFERENCES

Acheson, J. M., Capturing the Commons: Devising Institutions to Manage the Maine Lobster Industry, University Press of New England, 2003.

Agrawal, A. (2001), "Common Property Institutions and Sustainable Governance of Resources", World Development, 29 (10): 649-672.

Baland, J-M. and Platteau, J-P., Halting Degradation of Natural Resources. Is There a Role for Rural Communities? Clarendon Press, 1996.

Baland, J-M., Bardhan, P. and Bowles, S. (Eds.), Inequality, Cooperation, and Environmental Sustainability, Princeton University Press, 2006.

Ballester, C., Calvó-Armengol, A. and Y. Zenou (2006), “Who's Who in Networks. Wanted: The Key Player”, Econometrica, 74 (5): 1403–1417.

Banerjee, A., Chandrasekhar, A.G., Duflo, E. and Jackson, M.O. (2013), “The Diffusion of Microfinance”, Science 341 (6144).

Barabasi, A. (1999), “Emergence of Scaling in Random Networks”, Science 286 (5439): 509-512.

Barberis, N. and Shleifer, A. (2003), “Style Investing”, Journal of Financial Economics, 68: 161-199.

Bardhan, P., Ghatak, M., and Karaivanov, A. (2006), “Wealth Inequality and Collective Action”, Journal of Public Economics, 91 (9): 1843-1874.

Barrett, S. (1994), “Self-Enforcing International Environmental Agreements”, Oxford Economic Paper, 46: 878-894.

Bass, F. M. (1969) “A New Product Growth for Model Consumer Durables”, Management Science, 15 (5).

Bloch, F. and M. O. Jackson (2007),``The Formation of Networks with Transfers among Players,'' Journal of Economic Theory, 133 (1): 83-110.

Calvo-Armengol, A. (2004) “Job Contact Networks”, Journal of Economic Theory, 115: 191-206.

Calvo-Armengol, A. and Jackson, M.O. (2004) “The Effects of Social Networks on Employment and Inequality”, American Economic Review, 94 (3): 426-454.

Carraro, C. and D. Siniscalco (1993), "Strategies for the international protection of the environment," Journal of Public Economics, 52 (3): 309-328.

Carraro, C., Marchiori, C. and Sgobbi, A. (2007), “Negotiating on Water: Insights from Non-Cooperative Bargaining Theory”, Environment and Development Economics, 12 (2): 329-349.

Christakis, N and J.H. Fowler, “The collective dynamics of smoking in a large social network”, New England Journal of Medicine, 358 (21): 2249-2258.

Chung, N. N., Chew, L. Y. and Lai, C. H. (2013), “Influence of network structure on cooperative dynamics in coupled socio-ecological systems”, Europhysics Letters, 104 (2).

Conley, T., and Udry, C. (2001), “Social Learning Through Networks: The Adoption of New agricultural Technologies in Ghana”, American Journal of Agricultural Economics, 83: 668-673.

Currarini, S. (2007), "Network Design in Games with Spillovers", Review of Economic Design 10 (4): 305-326.

Currarini, S., Jackson, M. O. and Pin, P. (2009), “An Economic Model of Friendship: Homophily, Minorities and Segregation”, Econometrica, 77 (4): 1003–1045.

Currarini, S., Jackson, M. O. and Pin, P. (2010), “Identifying the roles of race-based choice and chance in high school friendship network formation”, Proceedings of the National Academy of Sciences. 107 (11): 4857–4861.

Currarini, S. and M. Morelli (2000), "Network Formation with Sequential Demands", Review of Economic Design 5 (3).

Currarini, S. and F. Feri, (2006), "Centralization versus Delegation: the Role of Externalities”, Research in Economics 60 (2): 112-119.

Demange, G. (2004) "On Group Stability in Hierarchies and Networks", Journal of Political Economy, 112 (4): 754-778.

Dixit, A. (2003), "Clubs with Entrapment", American Economic Review, 93 (5): 1824-1829.

Dutta, B. and S. Mutuswami (1997), "Stable Networks", Journal of Economic Theory, 76 (2): 322-344.

Eliott, M., Golub, B. and Jackson, M. O. (2013), “Financial Networks and Contagion”, mimeo.

Ernstson, H., Barthel, S., Andersson, E., and Borgstrom, S. T. (2010), “Scale-crossing Brokers and Network Governance of Urban Ecosystem Services: The Case of Stockholm”, Ecology & Society, 15 (4).

Galasso A., (2008), “Coordination and Bargaining Power in Contracting with Externalities”, Journal of Economic Theory 143: 558-570.

Galeotti, A., Goyal, S., Jackson, M.O., Vega-Redondo, F. and Yariv, L. (2010), “Network Games” The Review of Economic Studies, 77 (1): 218-244.

Genicot, G. and Ray, D. (2006), “Contracts and Externalities: How Things Fall Apart”, Journal of Economic Theory, 131: 71-100.

Gladwell, M., The Tipping Point: How Little Things Make a Big Difference. Little Brown, NY, 2000.

Gilles, J. L., Hammoudi, A., and Mahdi, M. (1992), “Oukaimedene, Morocco: A High Mountain Agdal”, in D. Bromley et al. (eds), Making the Commons Work: Theory, Practice, and Policy, pp. 229-46, ICS Press.

Goyal, S. and Moraga-Gonzalez, J. L. (2001), "R&D Networks," RAND Journal of Economics, 32 (4): 686-707.

Granovetter, M. (1978), “Threshold Models of Collective Behavior”, The American Journal of Sociology, 83 (6): 1420-1443.

Griliches, Z. (1957), “Hybrid Corn: An Exploration in the Economics of Technological Change”, Econometrica, 25 (4): 501-522.

Hardin, G. (1968), “The Tragedy of the Commons”, Science, 162 (3859): 1243-1248.

Heal, G. and Kunreuther, H. (2012), “Tipping Climate Negotiations”. In Climate Change and Common Sense: Essays in Honour of Tom Schelling, edited by Robert W. Hahn and Alastair Ulph. Joseph E. Aldy.

Hubert, F. and Cobanli, O. (2012), “Pipeline Power”, mimeo.

Ilkılıç, R. (2011), “Networks of Common Property Resources”, Economic Theory, 47: 105–134.

Jackson, M. O., Social and Economic Network, Princeton University Press, 2010.

Jackson, M. O. and Wolinsky, A. (1996), “A Strategic Model of Social and Economic Networks”, Journal of Economic Theory, 71 (1): 44-74.

Jackson, M. O. and van den Nouweland, A. (2005), “Strongly stable networks”, Games and Economic Behavior, 51 (2): 420-444.

Jackson, M.O. and Yariv, L. (2011), “Diffusion, Strategic Interaction, and Social Structure", in the Handbook of Social Economics (edited by Benhabib, Bisin, Jackson), North Holland Press 2011.

King, A., Managing Without Institutions: The Role of Communication Networks in Governing Resource Access and Control, Ph.D. thesis, University of Warwick, 2000.

Kranton, R. E. and Minehart, D. F. (2001), "A Theory of Buyer-Seller Networks," American Economic Review, 91 (3): 485-508.

Lade, S. J., Tavoni, A., Levin, S. A. and Schlüter, M. (2013), “Regime shifts in a social-ecological system”, Theoretical Ecology, 6 (3): 359-372.

Marchiori, C., Sayre Stratton, S., and Simon, L. (2012), “Bargaining and Devolution in the Upper Guadiana Basin”, Environmental and Resource Economics, 51 (3): 453-470.

McKean, M. A. (1986), “Management of Traditional Common Lands in Japan”, in Proceedings of the Conference on Common Property Resource Management, ed. National Research Council, pp. 533-90, National Academies Press.

McKean, M. A. (2000), “Common Property: What is It, What is It Good For, and What Makes It Work?”, in C. C. Gibson, M. A. McKean, and E. Ostrom (eds), People and Forests: Communities, Institutions, and Governance, pp. 27-50, MIT Press.

Molle, F., Wester, P., Hirsch, P., Jensen, J. R., Murray-Rust, H., Paranjpye, V., Pollard, S., van der Zaag, P. (2007), “River Basin Development and Management”, in Molden, D. (ed.), Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture, Earthscan.

Myerson, R. B. (1977), “Graphs and Cooperation in Games”, Mathematics of Operations Research, 2: 225-229.

Netting, R. McC. (1981), Balancing on an Alp: Ecological Change and Continuity in a Swiss Mountain Community, Cambridge University Press.

Nugent, J. B., and Sanchez, N. (1999), “The Local Variability of Rainfall and Tribal Institutions: the Case of Sudan”, Journal of Economic Behaviour and Organization, 39: 263-91.

Olson, M., The Logic of Collective Action: Public Goods and the Theory of Groups, Harvard University Press, 1965.

Ostrom, E. (2003), “How Types of Goods and Property Rights Jointly Affect Collective Action”, Journal of Theoretical Politics, 15 (3): 239-270.

Ostrom, E., Burger, J., Field, C. B., Norgaard, R. B., and Policansky, D. (1999), “Revisiting the Commons: Local Lessons, Global Challenges”, Science, 284 (5412): 278-282.

Platteau, J-P. (1991), “Traditional Systems of Social Security and Hunger Insurance: Past Achievements and Modern Challenges”, in E. Ahmad et al. (eds), Social Security in Developing Countries, pp. 112-70, Clarendon Press.

Pretty, J., and Ward, H. (2001), “Social Capital and the Environment”, World Development, 29: 209-227.

Ryan, B. and Gross, N. (1943), “The Diffusion of Hybrid Seed Corn in Two Iowa Communities”, Rural Sociology 8 (15).

Schoonmaker Freudnberger, M. (1993), “Regenerating the Gum Arabic Economy: Local-level Resource Management in Northern Senegal”, in J. Friedmann and H. Rangan (eds), In Defence of Livelihood: Cooperative Studies on Environmental Action, pp. 52-78, Kumarian Press.

Singleton, S. (1999), “Common Problems, Collective Action and Efficiency: Past and Present Institutions of Governance in Pacific Northwest Salmon Fisheries”, Journal of Theoretical Politics, 11 (3): 367-91.

Stein, C., Ernstson, H., and Barron, J. (2011), “A Social Network Approach to Analyzing Water Governance: The Case of the Mkindo Catchment, Tanzania”, Physics and Chemistry of the Earth, 36: 1085-1092.

Tavoni, A., Schlüter, M. and Levin, S. A. (2012), “The survival of the conformist: social pressure and renewable resource management”, Journal of Theoretical Biology, 299 (21): 152–161.

Trawick, P. (2003), “Against the Privatization of Water: an Indigenous Model for Improving Existing Laws and Successfully Governing the Commons”, World Development, 31 (6): 977-96.

Tulkens, H. and P. Chander, (1997), "The Core of an Economy with Multilateral Environmental Externalities," International Journal of Game Theory, 26 (3): 379-401.

Watts, D. J. (2002), "A simple model of global cascades on random networks". Proceedings of the National Academy of Sciences 99 (9): 5766–5720.

Weir, S. and Knight, J. (2004), “Externality Effects of Education: Dynamics of the Adoption and Diffusion of an Innovation in Rural Ethiopia”, Economic Development and Cultural Change, 53 (1): 93-113.

CMCC Research Papers

40

Centro Euro-Mediterraneo sui Cambiamenti Climatici

The Euro-Mediteranean Centre on Climate Change is a Ltd Company with its registered office and administration in Lecce and local units in Bologna, Venice, Capua, Sassari, Viterbo, Benevento and Milan. The society doesn't pursue profitable ends and aims to realize and manage the Centre, its promotion, and research coordination and different scientific and applied activities in the field of climate change study.

cmcc
Centro Euro-Mediterraneo
sui Cambiamenti Climatici